Ion-cyclotron-resonance measurement of the mass difference between tritium and helium-3

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The mass spectrum of the $^3He^+/^3T^+$ doublet has been measured. The mass difference is found to be $\Delta M = 18\,573 \pm 4$ eV.

The problem of determining the rest mass of neutrinos has recently attracted interest to the mass difference between tritium and helium-3 (Ref. 1). This letter reports an attempt to measure this mass difference by a method involving an ion cyclotron resonance and a Fourier transformation.

In this method,[2] the ions are spread out in a magnetic field by an rf pulse. The cyclotron motion of these ions induces a signal across the electrodes of a capacitor bracketing the volume containing the ions. This signal is measured.

In the experiments we use a Spectrospin CMS-47 ion-cyclotron-resonance spectrometer, which can detect masses from 12 to 3000 amu with an error of 10^{-6}. We expected that by working with suitable doublets and using an appropriate procedure to integrate the data we would be able to measure masses even more accurately. The most direct approach for the tritium-helium-3 problem would be to detect the $^3He^+$-T^+ atomic-ion doublet. Since the CMS-47 spectrometer is not capable of measuring masses below 12 amu, we constructed some electronic modules to synthesize frequencies near the frequencies of the cyclotron motion of these ions in a field of 4.686 T and to resonantly detect the signals from the ions at these frequencies during the time intervals between the excitation pulses. The sensitivity of the broad-band preamplifier of the CMS-47 spectrometer was not good enough to detect the signals from T^+ ions, so this preamplifier was modified for resonant detection; the effect was to improve the signal-to-noise ratio at this mass by a factor of ~ 30.

A 1:100 $^3He/T_2$ mixture was injected into the system for the measurements of the mass spectrum. The total pressure in the high-vacuum part of the apparatus was monitored by an ionization gauge calibrated for N_2. The total pressure in the system ranged from 5.5×10^{-9} to 8.0×10^{-9} Torr during the measurements. The residual gas pressure (primarily the components of air) ranged from 2×10^{-9} to 3×10^{-9} Torr. Tritium was admitted into the system through a palladium intake valve. The mixture was ionized by electrons with energies from 50 to 95 eV. The ionization time in each pulse of the cycle ranged from 0.25 to 0.5 s. The excitation amplitude was $\cong 30$ V at excitation pulse lengths ranging from 35 to 70 μs. The signal corresponding to the free cyclotron motion of the ions was detected for a time interval of 0.3 s. Each final spectrum was the result of the buildup of 200 spectra corresponding to a single ionization-excitation-detection cycle.

Figure 1 shows one of the spectra, obtained through a Fourier transformation of

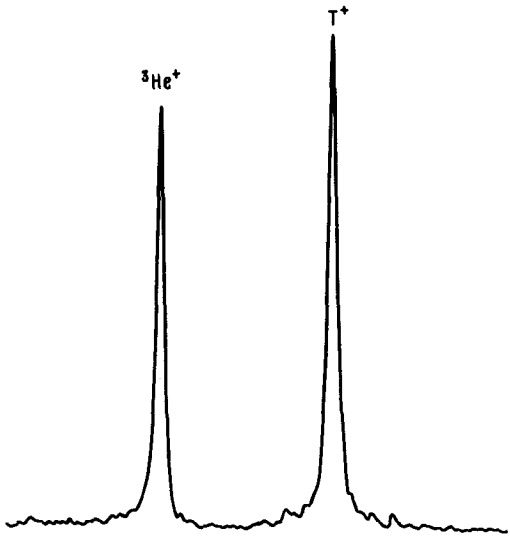

FIG. 1. Fourier spectrum of the signal corresponding to the ion cyclotron resonance of $^3He^+$ and $^3T^+$ ions. The resolution is 2 000 000.

the signal induced by the ensembles of $^3He^+$ and T^+ ions freely revolving in the magnetic field. To the best of our knowledge, the only direct detection of this doublet has been carried out by Mamyrin *et al.*,[3] who used a Mamyrin-Smith apparatus with a resolution of 7×10^{-6}. However, the very low signal-to-noise ratio in the spectra (those investigators attribute this problem to the β decay of tritium) prevented the use of these spectra to determine the mass difference. The resolution that we achieved at this doublet under the experimental conditions described above ranged from 3.5×10^{-7} to 1.5×10^{-7} and was determined by the decay of the signal caused by collisions with atoms and molecules of the injected mixture. The method used to build up the data, however, did in fact make it possible to improve the accuracy of the mass determination to a level considerably better than that corresponding to the resolution.

Table I shows the results of an analysis of six series of measurements including a

TABLE I.

Series	Mass difference between the $^3T^+$ and $^3He^+$ ions, eV	Number of spectra in the series
1	18571 (7)	20
2	18574 (9)	20
3	18572 (8)	30
4	18557 (17)	30
5	18589 (13)	25
6	18577 (15)	17

total of 142 spectra, measured at the various parameter values as outlined above. Shown in parentheses are the standard deviations σ_i for each series of measurements. When we use the formula

$$\Delta M_{av} \pm \sigma_{av} = \left(\sum_{i=1}^{6} \frac{1}{\sigma_i^2} \Delta M_i\right) / \left(\sum_{i=1}^{6} \frac{1}{\sigma_i^2}\right) \pm \left(\sum_{i=1}^{6} \frac{1}{\sigma_i^2}\right)^{-1/2}$$

to analyze the results of these six series of measurements, we find the mass difference 18 573 eV with an average standard deviation $\sigma_{av} = 4$ eV. In measuring the mass difference we took into account the possible systematic errors which are well known for the ion-cyclotron-resonance method. The average mass differences found in the various series of measurements do not correlate with the values of those experimental parameters which affect the dynamics of the ion motion in the cell, over the ranges of the parameters specified above.

The data on this mass difference in the literature, obtained quite recently and by a variety of methods, are spread over a range of about 100 eV (Refs. 4–7). The value found by us is close to the results found by Smith *et al.*[5] The accuracy achieved in these experiments shows that the ion-cyclotron-resonance method can be used to refine the overall nuclear mass scale.

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